

# Constraining the redshifted 21-cm signal with the unresolved soft X-ray background

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## ABSTRACT

We use the observed unresolved cosmic X-ray background (CXRB) in the 0.5–2 keV band and existing upper limits on the 21-cm power spectrum to constrain the high-redshift population of X-ray sources, focusing on their effect on the thermal history of the Universe and the cosmic 21-cm signal. Because the properties of these sources are poorly constrained, we consider hot gas, X-ray binaries and mini-quasars (i.e. sources with soft or hard X-ray spectra) as possible candidates. We find that (1) the soft-band CXRB sets an upper limit on the X-ray efficiency of sources that existed before the end of reionization, which is one-to-two orders of magnitude higher than typically assumed efficiencies, (2) hard sources are more effective in generating the CXRB than the soft ones, (3) the commonly assumed limit of saturated heating is not valid during the first half of reionization in the case of hard sources, with any allowed value of X-ray efficiency, (4) the maximal allowed X-ray efficiency sets a lower limit on the depth of the absorption trough in the global 21-cm signal and an upper limit on the height of the emission peak, while in the 21-cm power spectrum it sets a minimum amplitude and frequency for the high-redshift peaks, and (5) the existing upper limit on the 21-cm power spectrum sets a lower limit on the X-ray efficiency for each model. When combined with the 21-cm global signal, the CXRB will be useful for breaking degeneracies and helping constrain the nature of high-redshift heating sources.

**Key words:** cosmology: theory – dark ages, reionization, first stars – X-rays: binaries – X-rays: diffuse background.

## 1 INTRODUCTION

The cosmic X-ray background (CXRB) was the first cosmic background radiation to be discovered (Giacconi et al. 1962); however, its origin is not fully understood yet. Deep extragalactic X-ray surveys have resolved  $\approx 76$ –88 per cent of the CXRB into point sources, with the resolved fraction increasing at higher energies (Lehmer et al. 2012). It is now clear that the resolved CXRB is mostly produced by the integrated emission from active galactic nuclei (AGN) at  $z \leq 8$  and galaxies located at redshifts out to  $z = 2.6$  (Lehmer et al. 2012). However, a part of the CXRB remains unresolved and its origin is still undetermined. The largest fraction of the unresolved

CXRB is in the soft (0.5–2 keV) band, which has been explored by a number of X-ray missions (McCammon et al. 2002; Hickox & Markevich 2006; Lehmer et al. 2012); the unresolved fraction is 24.3 per cent of the total  $8.15 \pm 0.58 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2}$  background measured by *Chandra* (Lehmer et al. 2012) in this band. Future missions such as the proposed X-ray Surveyor (Weisskopf et al. 2015) and Athena<sup>1</sup> should be able to resolve this fraction, thus further constraining the contribution of distant and faint X-ray sources.

At present, the nature of the unresolved fraction of the CXRB is still debated. On the one hand, measurements of the X-ray background hint that in the soft-band normal galaxies may play

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an increasingly important role (Xue et al. 2011), likely dominating over AGN at fluxes below the detection limit of *Chandra* ( $\sim 5 \times 10^{-18}$  erg cm $^{-2}$  s $^{-1}$  in this band). Extrapolating the available data, Bauer et al. (2004) predicted that the number density of star-forming galaxies should overtake that of AGN at fluxes just below  $\sim 1 \times 10^{-17}$  erg cm $^{-2}$  s $^{-1}$ . In agreement, Lehmer et al. (2012) found that the normal-galaxy number counts rise rapidly at the faint end, compared to those of AGN, and contribute  $\approx 46$  per cent of the number counts in the soft band found in the *Chandra* Deep Field-South. On the other hand, an increasing number of faint and high-redshift quasars is being discovered with infrared, optical and X-ray surveys (Marleau et al. 2014; Moran et al. 2014; Lemons et al. 2015), supporting the idea that black holes may have a stronger than expected contribution to the CXRB (Dijkstra, Haiman & Loeb 2004; Madau & Haardt 2015).

Our understanding of the Universe, based on theoretical models and numerical simulations, suggests scenarios from which the excess of the soft X-ray background might naturally emerge. Current models show that the unresolved CXRB in the 0.5–2 keV band can be produced by faint point sources, either AGN or galaxies, with a possible additional contribution produced by truly diffuse components such as the intergalactic medium (IGM). In particular, Dijkstra et al. (2012) assumed a power-law X-ray spectral energy distribution (SED) of sources and varied their X-ray luminosity per unit star formation rate (SFR) with redshift, showing that faint galaxies at redshifts up to  $z = 10$  can fully account for the unresolved portion of the CXRB; Cappelluti et al. (2012) investigated the power spectrum of the unresolved CXRB in the soft band and interpreted the signal as a mixture of contributions from low-luminosity AGN ( $\sim 20$  per cent), galaxies up to  $z = 10$  ( $\sim 25$  per cent), and thermal emission of the IGM ( $\sim 55$  per cent), where the contribution of galaxies was modelled with a power-law SED and normalized using the observed X-ray luminosity function; Madau & Haardt (2015) showed that a population of high-redshift quasars and AGN with a piece-wise power-law SED (Haardt & Madau 2012) can explain  $\sim 60$  per cent of the unresolved CXRB at  $\sim 2$  keV. The latter possibility is particularly interesting since, according to Madau & Haardt (2015), such a population of sources could also fully reionize hydrogen and helium if their UV emissivity is normalized to the recent results of Giallongo et al. (2015).

Naturally, it is tempting to explain the excess in the soft CXRB as a contribution of high-redshift X-ray sources (McQuinn 2012; Christian & Loeb 2013) in galaxies existing before the end of the Epoch of Reionization (EoR) at  $z_{\text{re}} \sim 6\text{--}9$  (Becker et al. 2015; Planck Collaboration XIII 2015). These galaxies emit UV and X-ray photons which ionize and heat the intergalactic gas. While UV radiation has a small mean free path in the neutral medium and, thus, reionizes gas close to the source (Wyithe & Loeb 2003a), X-ray photons travel hundreds of comoving megaparsecs away, heating and partially ionizing the neutral gas far from the sources (Mirabel et al. 2011). In most of the currently discussed models of reionization, UV photons are more efficient than X-rays in ionizing the medium, and reionization proceeds inside-out down to the scale of the H II bubbles (Barkana & Loeb 2004), while X-rays only preheat the IGM. This picture, however, depends on the relative normalization of the two processes and there are scenarios in which X-rays are more efficient than the UV photons in driving reionization, and it proceeds more homogeneously, with significant smoothing up to the typical X-ray mean free path (McQuinn 2012; Mesinger, Ferrara & Spiegel 2013; Majumdar et al. 2016). The hardest X-rays emitted by a population of high-redshift sources are expected to have such large mean free paths that they are never absorbed by the

IGM and, thus, contribute to the unresolved soft CXRB observed today.

The extent to which the first X-ray sources contribute to the CXRB, as well as their role in the thermal history and reionization of the IGM, depends on their nature. At present, these sources are poorly constrained due to the lack of observations and there are several possible candidates, including X-ray binaries (XRBs; Power et al. 2009, 2013; Mirabel et al. 2011; Fragos et al. 2013), mini-quasars (Madau et al. 2004), and hot gas in galaxies, hard photons emitted as a result of high-redshift supernovae activity (Oh 2001), as well as more exotic candidates such as annihilating dark matter (Cirelli, Iocco & Panci 2009). The SED of X-ray photons emitted in each case depends on the character of the sources, varying from a hard spectrum that peaks at the photon energy of  $\sim 3$  keV, as in the currently favoured case of XRBs (Mirabel et al. 2011; Fragos et al. 2013; Fialkov, Barkana & Visbal 2014), to a soft power-law SED expected from hot gas heated by supernova explosions and winds within galaxies (e.g. Furlanetto 2006).

The details of cosmic heating and reionization affect the redshifted 21-cm signal of neutral hydrogen (e.g. see Furlanetto, Oh & Briggs 2006; Pritchard & Furlanetto 2007; Ripamonti, Mapelli & Zaroubi 2008; Pritchard & Loeb 2012). This radio signal, which is hoped to be the richest future probe of astrophysics and cosmology at high redshifts, is sensitive to the spectrum and nature of the early X-ray sources (Fialkov & Barkana 2014; Fialkov, Barkana & Visbal 2014; Mirocha 2014; Pacucci et al. 2014; Fialkov, Barkana & Cohen 2015; Ewall-Wice et al. 2016). In this paper, we explore the redshifted 21-cm signal while constraining the luminosity of the high-redshift X-ray sources by the observed soft CXRB. The CXRB constraint yields an upper limit on the X-ray efficiency of each type of source and thus allows us to estimate the maximal possible effect of cosmic heating on the 21-cm signal. Such a limit has not been quoted before, although the effect of strong soft X-ray sources on the 21-cm signal has been studied (Pritchard & Loeb 2012; Mesinger et al. 2013; Pacucci et al. 2014). Moreover, we improve over the existing works by considering the CXRB limits on two new types of X-ray sources, namely, realistic XRBs and mini-quasars, both with a hard SED. Given the great current uncertainty about the properties of early galaxies, this is an essential constraint that will help guide the search for the radio signal by existing, planned and upcoming radio telescopes designed to probe the 21-cm signal out to  $z \sim 30$ , such as the Square Kilometre Array (SKA; Koopmans et al. 2015), the Hydrogen Epoch of Reionization Array (HERA),<sup>2</sup> Large Aperture Experiment to Detect the Dark Age (LEDA; Bernardi et al. 2016), the Experiment to Detect the Global EoR Step (EDGES; Bowman & Rogers 2010), the Dark Ages Radio Explorer (DARE; Burns et al. 2012), the Shaped Antenna measurement of the background Radio Spectrum (SARAS; Patra et al. 2013), the SCI-HI experiment (Voytek et al. 2014), the Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER; Parsons et al. 2014), Giant Metrewave Radio Telescope (GMRT; Paciga et al. 2013), the Murchison Widefield Array (MWA; Bowman et al. 2013), the LOw-Frequency ARray (LOFAR; van Haarlem et al. 2013), and the New Extension in Nançay Upgrading LOFAR (NenuFAR; Zarka et al. 2012).

The paper is organized as follows: in Section 2, we describe the simulation and model assumptions used in this work; in Section 3, we (1) use the observed unresolved CXRB to establish the upper bound on the X-ray efficiency of high-redshift sources, and (2)

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apply the existing upper limits on the 21-cm power spectrum to set the lower limit on the X-ray efficiency; in Section 4, we present our results for the thermal history, partial X-ray ionization, and the 21-cm signal; finally, we summarize and conclude in Section 5. Throughout this paper, we use cosmological parameters as measured by the Planck Collaboration (Planck Collaboration XVI 2013).

## 2 SIMULATED UNIVERSE

We simulated large cosmological volumes of  $384^3 \text{ Mpc}^3$  of the high-redshift universe using a hybrid simulation, first introduced by Visbal et al. (2012) and described in detail by Fialkov et al. (2014); we describe it briefly here. Using the known statistical properties of the initial density field, we generated a random realization of the initial overdensity (with periodic boundary conditions) and the supersonic relative velocities between the gas and dark matter (Tsaliakhovich & Hirata 2010; Tsaliakhovich, Barkana & Hirata 2011; Fialkov 2014) in a cubic volume. Given the large-scale density distribution, we then computed the gas fraction in star-forming haloes in each cell as a function of time. In our simulation, the SFR, found following the extended Press–Schechter formalism (Barkana & Loeb 2004), is modified by the large-scale density fluctuations and the supersonic relative velocities. Throughout the simulation, we assume Population II stars with standard spectra (from Leitherer et al. 1999; Barkana & Loeb 2005) and a star formation efficiency of 5 per cent. We also account for the effect of photoheating feedback on the amount of gas available for star formation (Cohen, Fialkov & Barkana 2016a). Next, we use the stellar distribution to determine the X-ray heating rate, ionization, free electron fraction and the intensity of the Ly- $\alpha$  background in each cell. To this end, we first smooth the stellar density field at each redshift in shells around each cell. We assume the flux of X-ray and Ly- $\alpha$  photons emitted from each shell to be proportional to the SFR, which is in turn proportional to the time derivative of the amount of gas in star-forming haloes. We then compute the heating and ionization rates as well as the intensity of the Ly- $\alpha$  background by integrating over all the shells seen by each cell (using rates from Furlanetto & Stoever 2010). In this integral, the contribution of each cell to the rate at a given central cell is computed at the time-delayed redshift as seen by the central cell. Given the X-ray heating and ionization rates versus redshift at each cell, we integrated to get the gas temperature and free electron fraction as a function of time. To include UV reionization, we set each cell to be fully reionized if some sphere around it contains enough ionizing photons to self-reionize (Furlanetto, Zaldarriaga & Hernquist 2004). With this simulation, we followed the thermal history of the universe and made predictions for the observable soft-band CXRB and the 21-cm signal from a wide range of redshifts,  $z = 6\text{--}40$ , as discussed in Sections 3 and 4.

This tool based on a combination of numerical simulation and analytical calculations has enough flexibility to explore various parameters of the unconstrained high-redshift environment such as the X-ray efficiency ( $f_X$ ) and SED of the first heating sources, the minimal mass of star-forming haloes and the reionization history. To probe the parameter space, we consider two cases in which the IGM is reionized by UV photons emitted by early galaxies. In the ‘late reionization’ case, the universe is fully reionized by  $z_{\text{re}} = 6.2$ , with the value of the electron optical depth falling in the range  $\tau = 0.059\text{--}0.074$  which is within  $1\sigma\text{--}2\sigma$  of the latest Planck result,  $\tau = 0.058 \pm 0.012$ , (Planck Collaboration XL VII 2016); while in the second case, ‘early reionization’,  $z_{\text{re}} = 8.5$  and  $\tau$  falls within  $\sim 3\sigma$  of the Planck measurement. Late versus early reionization scenarios are obtained by varying the ionizing efficiency of sources

in each model. When we normalize the X-ray emission (see below), we also use the redshift of full reionization as the cut-off time for this normalization; in this way, the two cases with different values of  $z_{\text{re}}$  also serve to probe which redshifts are really constrained by the X-ray background. Next, we consider two possible cases for the typical galactic halo mass: including star formation in haloes down to the lowest mass that allows for efficient atomic cooling, which we term the ‘atomic cooling’ case, or adopting a minimum halo mass for star formation that is 10 times larger (allowing for the possibility of strong feedback in small haloes), which we refer to as ‘massive haloes’. Finally, we consider three types of X-ray sources: XRBs that have a hard SED (Fragos et al. 2013; Fialkov et al. 2014), sources with a soft power-law SED of spectral index  $\alpha_S = 0.5$  (where the luminosity  $L$  follows  $dL/d\log\nu \propto \nu^{-\alpha_S}$ ; Furlanetto 2006), and mini-quasars, i.e. central black holes in early star-forming galaxies, which we discuss in greater detail in Section 2.1.

The efficiency of hot gas or XRBs is defined via the relation between the bolometric X-ray luminosity  $L_X$  and the SFR of the galaxy

$$\frac{L_X}{\text{SFR}} = 3 \times 10^{40} f_X \text{ erg s}^{-1} \text{ M}_{\odot}^{-1} \text{ yr}, \quad (1)$$

where the standard value of the X-ray efficiency is  $f_X = 1$  (Furlanetto et al. 2006; Fragos et al. 2013). This relation is based on observations of nearby starburst galaxies and XRBs (Grimm, Gilfanov & Sunyaev 2003; Gilfanov, Grimm & Sunyaev 2004; Mineo, Gilfanov & Sunyaev 2012a,b), and the standard normalization for XRBs (with  $f_X = 1$ ) includes an order-of-magnitude increase in this ratio at the low metallicity expected for high-redshift galaxies (Fragos et al. 2013).

While the numerical factor in equation (1) was derived for XRBs over the range 0.2–95 keV (Fragos et al. 2013), in this paper, we chose a common normalization for soft and hard sources for simplicity. For easier comparison with other work in the literature, we list here the luminosities (for  $f_X = 1$ ) in the 0.2–30 keV and 0.5–8 keV bands, for both the hard and the soft SEDs:  $L_{0.2-30}^{\text{soft}}/\text{SFR} = 3 \times 10^{40}$ ,  $L_{0.2-30}^{\text{hard}}/\text{SFR} = 2.8 \times 10^{40}$ ;  $L_{0.5-8}^{\text{soft}}/\text{SFR} = 1.6 \times 10^{40}$ ,  $L_{0.5-8}^{\text{hard}}/\text{SFR} = 2.4 \times 10^{40}$ . Note that in our late EoR scenario most of the X-rays that contribute to the CXRB originate near  $z_{\text{re}} = 6.2$ , in the rest-frame frequency range of 3.6–14.4 keV where the corresponding luminosities are  $L_{3.6-14.4}^{\text{soft}}/\text{SFR} = 3.9 \times 10^{39}$  and  $L_{3.6-14.4}^{\text{hard}}/\text{SFR} = 1.2 \times 10^{40}$ . In the early EoR scenario, i.e.  $z_{\text{re}} = 8.5$ , *Chandra*’s soft-band probes the rest-frame 4.7–19 keV range where the luminosities amount to  $L_{4.7-19}^{\text{soft}}/\text{SFR} = 3.4 \times 10^{39}$  and  $L_{4.7-19}^{\text{hard}}/\text{SFR} = 8.7 \times 10^{39}$ .

### 2.1 Mini-quasars

High-redshift black holes are expected to be much lighter than the ones observed today in Milky Way size haloes,  $\sim 10^2\text{--}10^4 \text{ M}_{\odot}$  compared to  $\sim 10^6\text{--}10^9 \text{ M}_{\odot}$ . Until recently, the early population of high-redshift black holes with such small masses was considered purely speculative. However, the latest observations find black holes with masses in the  $10^2\text{--}10^6 \text{ M}_{\odot}$  range in dwarf metal-poor galaxies which may resemble the high-redshift environment. In particular, Moran et al. (2014) used the Sloan Digital Sky Survey to find 28 AGN in nearby low-mass, low-luminosity dwarf galaxies and estimated the minimum black hole mass to fall mainly in the  $10^3\text{--}10^4 \text{ M}_{\odot}$  range, showing that AGN in dwarf galaxies are not as rare as previously thought; Marleau et al. (2014) studied the infrared signature of active nuclei in nearby dwarf galaxies and found black hole masses of  $10^2\text{--}10^6 \text{ M}_{\odot}$ ; while Lemons et al. (2015) found that

**Table 1.** For each scenario of structure formation and reionization (column 1; four total scenarios), we list the SED (column 2),  $f_X$  (column 3) set so that the high-redshift sources produce the entire unresolved CXRB in the 0.5–2 keV band of  $2.51 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2}$  (Cappelluti et al. 2012), the heating transition redshift  $z_h$  (column 4), the X-ray ionization fraction at the end of the UV reionization (column 5), the UV contribution to the optical depth (column 6) and the total optical depth  $\tau_{\text{tot}}$  due to the UV and X-ray ionization (column 7), the minimal temperature of the global 21-cm signal ( $T_{21}^{\text{min}}$ , column 8), and the redshift at which it occurs ( $z_{\text{min}}$ , column 9), the maximal temperature of the global 21-cm signal in emission ( $T_{21}^{\text{max}}$ , column 10), and the redshift at which it occurs ( $z_{\text{max}}$ , column 11).

Model	SED	$f_X$	$z_h$	$x_{\text{ion}}^X (\%)$	$\tau_{\text{UV}}$	$\tau_{\text{tot}}$	$T_{21}^{\text{min}}$ (mK)	$z_{\text{min}}$	$T_{21}^{\text{max}}$ (mK)	$z_{\text{max}}$
Massive	Hard	14.7	13.5	7.6	0.0597	0.0609	− 85.3	17.0	20.8	10.7
Late EoR	Soft	41.4	17.0	27.3	0.0601	0.0688	− 29.7	18.8	26.2	12.8
$z_{\text{re}}^{\text{UV}} = 6.2$	MQ	12.1	13.0	6.4	0.0597	0.0606	− 99.7	16.7	19.6	10.4
Massive	Hard	79.2	15.7	9.3	0.0831	0.0850	− 42.7	18.5	22.7	12.8
Early EoR	Soft	187.7	18.8	34.5	0.0833	0.0934	− 15.1	20.3	26.3	14.3
$z_{\text{re}}^{\text{UV}} = 8.5$	MQ	87.9	15.4	8.6	0.0831	0.0847	− 47.5	18.2	22.2	12.5
Atomic	Hard	10.8	16.2	10.5	0.0739	0.0756	− 107.4	20.6	23.0	13.0
Late EoR	Soft	29.5	20.1	40.0	0.0746	0.0859	− 48.8	22.7	29.7	15.6
$z_{\text{re}}^{\text{UV}} = 6.2$	MQ	11.4	14.0	7.5	0.0738	0.0747	− 147.4	19.3	17.7	11.6
Atomic	Hard	44.4	18.5	13.5	0.0957	0.0990	− 68.8	21.9	25.9	15.2
Early EoR	Soft	102.4	21.9	39.1	0.0961	0.1111	− 29.2	24.1	30.4	17.3
$z_{\text{re}}^{\text{UV}} = 8.5$	MQ	74.4	16.9	10.5	0.0956	0.0977	− 99.0	20.9	22.5	14.0

relatively many hard X-ray sources in dwarf galaxies are ultraluminous. The abundance and brightness of these sources suggest that mini-quasars and high-redshift AGN may have had a stronger impact on reionization than what is usually assumed.

Here, we use the internal feedback model for the black hole mass (Wyithe & Loeb 2003b) and follow the discussion in Fialkov et al. (2014) to model the population of high-redshift mini-quasars and their impact on the heating and reionization of the universe. Thus, we find the ratio of the average X-ray luminosity of the central mini-quasar to that of XRBs in the same halo to be

$$\frac{L_{\text{MQ}}}{L_{\text{XRB}}} \sim 0.1 \left( \frac{0.05 f_X^{\text{MQ}}}{f_X f_*} \right) \left( \frac{M_h}{10^8 M_\odot} \right)^{2/3} \frac{1+z}{10}, \quad (2)$$

where we assumed, as in the case of XRBs, that on average 25 per cent of the mini-quasar X-rays in the relevant wavelengths are not absorbed in the interstellar medium (ISM) of the host galaxy. Here, we needed this non-absorbed fraction in order to compare between XRBs (for whom ISM absorption is implicitly included in the spectrum, which is based on observations) to mini-quasars (for which we estimated the intrinsic emitted energy using a theoretical model). We note that, by using the XRB spectrum, we assume (like Fragos et al. 2013) that this absorption at high redshifts is similar to that at the low redshifts of the observations. In the ratio in equation (1),  $f_X^{\text{MQ}}$  parameterizes the uncertainty in the X-ray efficiency of mini-quasars with  $f_X^{\text{MQ}} = 1$  being its standard value. For simplicity, in the rest of this paper we omit the superscript MQ when talking about the X-ray efficiency of mini-quasars. Using equation (1), we can express the X-ray luminosity of a mini-quasar formed in a halo of mass  $M_h$  in terms of the SFR in the same halo.

Compared to XRBs, the X-ray luminosity of a mini-quasar is weighted by an additional factor of  $(M_h/10^8 M_\odot)^{2/3}$ . Because of this additional factor, the contribution of mini-quasars to the X-ray background is expected to be negligible compared to that of XRBs at high redshifts ( $z \gg 8$ ) where the typical halo mass is small, but it becomes important at lower redshifts ( $z \ll 8$ ) at which larger haloes form bigger black holes. When mini-quasar emission is modelled as a multicolour (Shakura & Sunyaev 1973) accretion disc, these sources are expected to have hard SEDs that are similar to those of XRBs, due to the weak dependence of the X-ray spectrum on the

black hole mass (Tanaka, Perna & Haiman 2012). Therefore, we use the same SED for XRBs and mini-quasars in our calculation.

### 3 LIMITS ON THE X-RAY EFFICIENCY

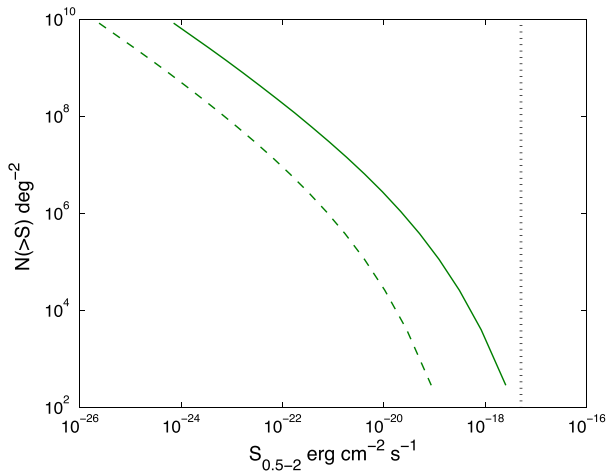
In this work, we rely on the observed intensity of the unresolved CXRB in the 0.5–2 keV band as measured by *Chandra* (Lehmer et al. 2012) to set the maximum possible X-ray efficiency for each type of the considered X-ray sources. Following the model developed by Cappelluti et al. (2012), we assume that the extragalactic contribution amounts to  $2.51 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2}$  and is provided solely by the pre-reionization sources. This normalization gives the maximal value of X-ray efficiency of the high-redshift heating sources that does not violate the observed soft-band CXRB.

The values of  $f_X$  that we obtain by comparing the simulated background to the observed one are listed in the third column of Table 1 for each case of the reionization history and SED specified in the first two columns of the table. We find that in order to produce the detected unresolved X-ray background,  $f_X$  must be one to two orders of magnitude larger than the standard value,  $f_X \sim 1$ , normally assumed in the literature for the efficiency of the high-redshift sources, although even higher values of  $f_X$  have been considered (Christian & Loeb 2013; Mesinger et al. 2013; Pacucci et al. 2014).

We find that hard sources, and in particular mini-quasars, are more efficient in producing the CXRB in the soft band, in that they require an X-ray efficiency that is a factor of a few lower than that of soft sources. This is because most of the energy emitted by soft X-ray sources redshifts to frequencies much lower than the observed band. Therefore, a high efficiency is needed in that case in order to increase the number of photons that eventually redshift into the relevant energy range. On the other hand, in the case of the hard X-ray sources (XRBs and mini-quasars), the SED peaks at  $\sim 3$  keV and, at least for sources at  $z \sim 6$  existing just before the end of reionization in our late reionization scenario, the observed 0.5–2 keV band probes the energy range around the peak of the SED, and a lower efficiency is sufficient to produce the observed CXRB.

Even though the maximum X-ray efficiencies that we find are relatively high, the population of pre-reionization sources with such efficiencies is still very dim and cannot be resolved into point sources



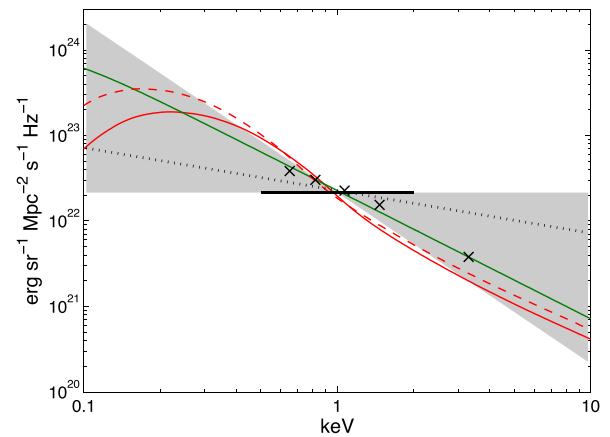


**Figure 1.** Cumulative X-ray number counts at  $z = 6.2$  for the soft band with atomic cooling haloes and a soft SED, for  $f_X = 29.5$  (solid) or  $f_X = 1$  (dashed). The vertical dotted line shows the detection limit of *Chandra* in the soft band.

by *Chandra*. In Fig. 1, we show the cumulative number counts expected for such a population for the case of the high-redshift X-ray sources with a soft SED, with  $f_X = 29.5$  (and  $f_X = 1$  for comparison). As we see from the figure, the fluxes are well below the detection limit of the satellite,  $\sim 5.1 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$ , and, therefore, it is correct to consider these sources as unresolved ones, as we do in this work.

Another trend in the normalized X-ray efficiencies  $f_X$  in Table 1 is that the early reionization cases correspond to a higher  $f_X$ . This is not due to reionization itself but since (as noted in Section 2) we use the end of reionization as a convenient cut-off redshift for the X-ray source population, in order to probe how various redshifts are constrained. Thus, in the case of early reionization, when the X-ray sources that we are considering are assumed to be cut-off below  $z = 8.5$ , we require a very high normalization at  $z > 8.5$  in order to explain the observed CXRB. Another way to express this is that sources at higher redshifts are less strongly constrained, i.e. a higher maximal  $f_X$  is allowed for them without violating the observed CXRB. The  $f_X$  values shown in Table 1 can be seen as upper limits on a hypothetical high-redshift population of X-ray sources that formed down to  $z = 6.2$  or  $8.5$ , and may have had a much higher X-ray efficiency than is typical for low-redshift galaxies. In the case of massive haloes, there are fewer galaxies at any given redshift than in the atomic case, so the X-ray efficiency must be higher in order to explain the same, fixed, level of the observed CXRB.

The shape of the unresolved CXRB in the 0.5–2 keV band shown in Fig. 2 is poorly constrained by observations, and only a general trend can be extracted from the available data at the moment. The best fit to *Chandra* data proposed by Hickox & Markevich (2006) is a power law with a spectral index of  $\alpha = 0.5$  (but note that the amplitude of X-ray number counts, not the slope, was a free parameter in this fit). Another constraint on the shape of the CXRB comes from the data collected by the *Röntgenstrahlen* (*ROSAT*) satellite (Hasinger et al. 1993; McCammon et al. (2002) reported the spectral structure of the unresolved background measured in the  $\sim 0.65$ – $3.3$  keV range. These data were extracted after subtracting the local thermal component, the contribution of oxygen lines from the *ROSAT* data, and accounting for the AGN directly observed by the deep surveys with the satellite. However, due to a



**Figure 2.** Extragalactic contribution to the unresolved X-ray background in the 0.5–2 keV band versus the energy of the photon. Assuming atomic cooling haloes, we show the cases of a hard spectrum for early (red dashed) or late (red solid) reionization, and a soft SED for early (green dashed) or late (green solid) reionization; the two soft SED cases lie on top of each other. We calibrate the CXRB in the soft band 0.5–2 keV to the value of  $2.51 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2}$  (Cappelluti et al. 2012), showing the average intensity with the black horizontal bar in the plot. We also show the shape of the ‘absolute’ unresolved soft extragalactic X-ray background from McCammon et al. (2002, crosses) normalized to the same value. The shaded area spans the range of slopes considered by Dijkstra et al. (2012) for the CXRB (between  $\alpha = 0$  and 2), and the black dotted curve has the best-fitting spectral index from *Chandra* data (Hickox & Markevich 2006),  $\alpha = 0.5$ .

considerable discrepancy in the normalization of the CXRB measured by *Chandra* and *ROSAT*, which most likely arises from cosmic variance and systematics, it is unclear if the residual found in *ROSAT* data can be fully attributed to the cosmic background. Therefore, we only show the unresolved CXRB measured by *ROSAT* (black crosses in Fig. 2) with its normalization re-scaled to the value of  $2.51 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2}$  in the 0.5–2 keV band.

Despite the discrepancy in the normalization and large uncertainties in the *ROSAT* data, it is still interesting to compare the shape of the CXRB found by McCammon et al. (2002) to what is extracted from our simulations (Fig. 2). This shape is in good agreement with the CXRB which we get using our soft SED while our hard SED yields a slightly steeper frequency dependence; the fit to *Chandra* data is somewhat softer than predicted by our models. Because observational constraints on the slope are so poor and inconclusive, a wide variety of possible SEDs are considered in the literature when modelling high-redshift populations. For instance, Dijkstra et al. (2012) explored a wide range of spectral indices,  $\alpha = 0$ – $2$ , of high-redshift galaxy SEDs when trying to reproduce the observed CXRB (this range is marked as the shaded area in Fig. 2). Both our cases (soft and hard SEDs) yield a CXRB with slopes which (approximately) fall within this range. We note that our normalization at 0.5–2 keV is consistent with Moretti (2012), but their data suggest a somewhat harder spectrum towards higher energies than the range shown in Fig. 2.

A lower limit on the X-ray efficiency can in some cases be extracted from the upper limit on the 21-cm power spectrum (Ali et al. 2015; Pober et al. 2015). As we will see in the next section, the hotter is the IGM, the smaller is the amplitude of the 21-cm signal seen against the cosmic microwave background (CMB). Consequently, a very cold IGM results in fluctuations of large amplitude that can be ruled out by existing observations. Parsons et al. (2014) were the

**Table 2.**  $f_X = 1$  case. For each scenario of structure formation and reionization (column 1), we show the SED (column 2), the heating transition redshift  $z_h$  (column 3), the X-ray ionization fraction at the end of the UV reionization (column 4), the minimal temperature of the global 21-cm signal ( $T_{21}^{\min}$ , column 5), and the redshift at which it occurs ( $z_{\min}$ , column 6).

Model	SED	$z_h$	$x_{\text{ion}}^X (\%)$	$T_{21}^{\min} \text{ (mK)}$	$z_{\min}$
Massive	Hard	9.7	0.7	-167.7	14.9
Late EoR	Soft	12.2	2.3	-121.3	16.1
$z_{\text{re}}^{\text{UV}} = 6.2$	MQ	9.5	0.6	-174.3	14.6
Massive	Hard	9.6	0.2	-163.9	14.9
Early EoR	Soft	12.1	0.5	-120.9	16.1
$z_{\text{re}}^{\text{UV}} = 8.5$	MQ	9.3	0.1	-171.7	14.6
Atomic	Hard	12.0	1.3	-169.6	18.2
Late EoR	Soft	14.8	4.5	-134.8	19.6
$z_{\text{re}}^{\text{UV}} = 6.2$	MQ	10.1	0.8	-201.3	16.6
Atomic	Hard	12.0	0.5	-169.6	18.3
Early EoR	Soft	14.8	1.6	-134.7	19.7
$z_{\text{re}}^{\text{UV}} = 9$	MQ	10.0	0.2	-202.9	16.5

first to place limits on X-ray heating with the 21-cm power spectrum using the data collected by the PAPER experiment. Current upper limit on the 21-cm power spectrum of  $\sim 500 \text{ mK}^2$  at  $z = 8.4$  in the range of wavenumbers  $k = 0.15\text{--}0.5 \text{ h Mpc}^{-1}$  (Ali et al. 2015; Pober et al. 2015) yields  $f_X \gtrsim 0.0095$  (0.0023) in the case of a hard (soft) SED for our atomic cooling case and  $f_X \gtrsim 0.036$  (0.01) in the case of massive haloes for the late EoR scenario. Our early reionization scenario is not constrained by this measurement since the universe is fully ionized by  $z_{\text{re}} = 8.5$  and the 21-cm signal at lower redshifts vanishes for all heating scenarios.

## 4 RESULTS

### 4.1 Ionization and heating

In this section, we present our quantitative results for the possible consequences of having strong X-ray sources at high redshift as currently allowed by the CXRB. One obvious result is that X-ray sources with a high X-ray efficiency heat up the IGM much earlier than is normally expected. The moment when the gas heats up to the temperature of the CMB (the cosmic heating transition), of which redshift we denote  $z_h$ , happens earlier in the models where  $f_X$  is set to its upper limit compared to the predictions for the  $f_X = 1$  case. In the case of the soft SED, late reionization and atomic cooling, this transition happens a  $\Delta z_h = 5.3$  earlier, while in the case of XRBs the advance is  $\Delta z_h = 4.2$ . In Table 1, we list  $z_h$  for all the considered cases with the maximum  $f_X$ , while Table 2 shows the same cases but for  $f_X = 1$ .

It is interesting to see if the saturated heating assumption, which is often used in numerical simulations, holds during reionization when the CXRB limit is applied. Saturated heating is the assumption that the gas is much hotter than the CMB, i.e.  $1 - T_{\text{CMB}}/T_K \sim 1$ . If this assumption is valid, then the heating history can be ignored when reionization is considered. Considering our models with  $f_X$  values from Table 1, we find that in the case of a hard SED the value of the factor  $1 - T_{\text{CMB}}/T_K$  is far from unity at the beginning of the EoR when the universe is  $\sim 5$  per cent ionized. In particular in the case of late (early) reionization and atomic cooling, this factor (when averaged over a simulated box) is 0.6 (0.59) at  $x_{\text{H I}} = 95$  per cent for XRBs and  $-0.36$  ( $-0.1$ ) for mini-quasars. In the case of late (early) reionization and massive haloes, this factor is 0.66 (0.75)

for XRBs, and 0.5 (0.7) for mini-quasars. By the mid-point of UV reionization,  $1 - T_{\text{CMB}}/T_K \gtrsim 0.95$  in all the simulated cases from Table 1 and, hence, the saturated heating assumption applies during the second half of reionization. The CXRB-normalized models with a soft SED yield  $1 - T_{\text{CMB}}/T_K \gtrsim 0.97$  already at an ionization fraction of 5 per cent.

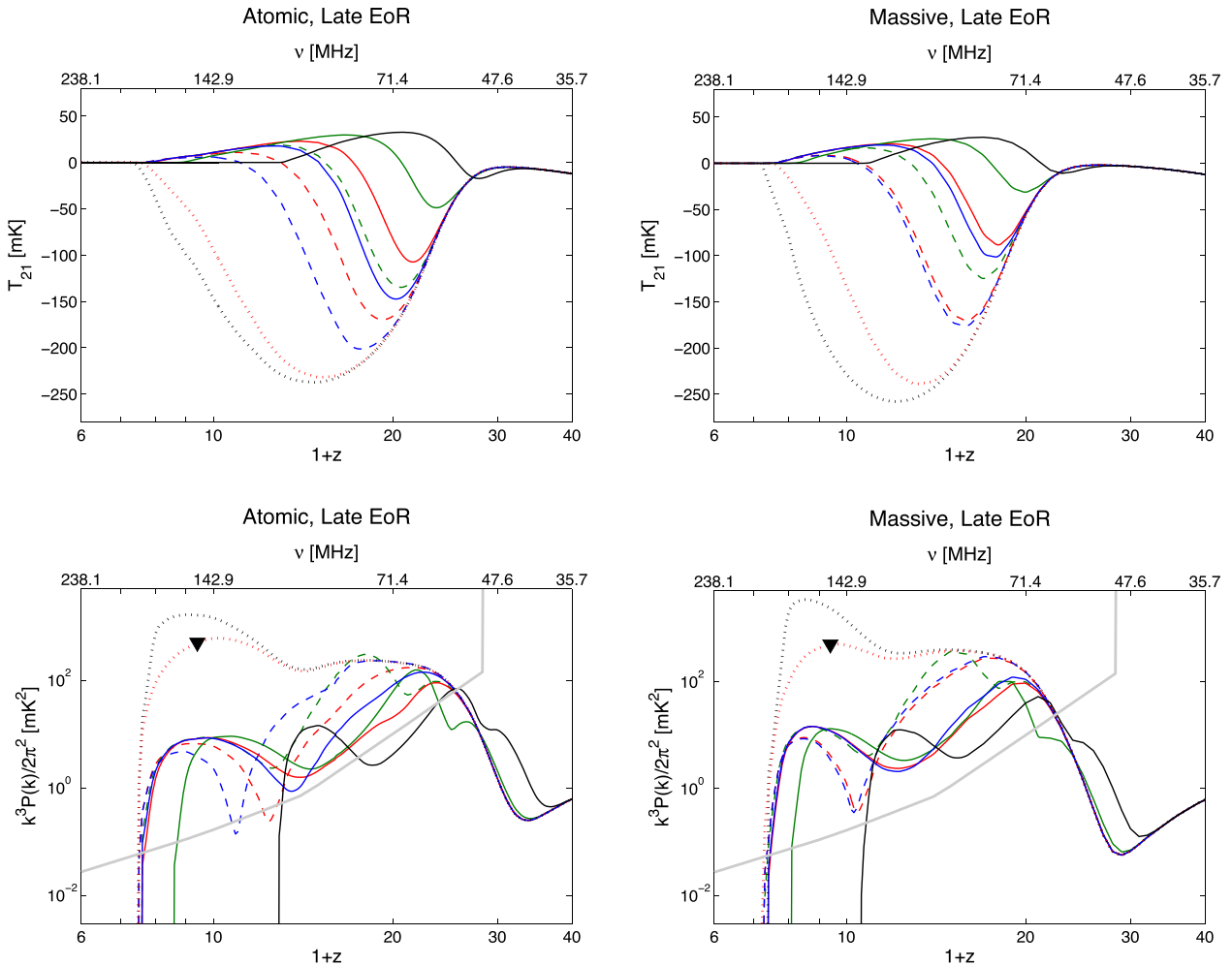
Along with heating, X-rays partially ionize the neutral medium, competing with the UV photons in powering reionization. The efficiency of X-rays versus UV in ionizing the cosmic gas depends on the values of the escape fraction and the X-ray efficiency. Here, we keep the former parameter fixed in each case by fixing the redshift at which reionization is completed by the UV photons, while varying the latter. In the standard case of  $f_X = 1$ , the main source of ionization is UV photons while X-rays are expected to yield only a small contribution, ionizing the gas only up to a few per cent when reionization is completed by UV. To emphasize this, we list the level of the partial ionization by X-rays (within the final remaining neutral regions just before they are reionized),  $x_{\text{ion}}^X$ , at the end of reionization powered by UV photons, in the fourth column of Table 2. The value of  $x_{\text{ion}}^X$  does not rise above 4.5 per cent.

On the other hand, with  $f_X$  set to its maximum by normalization to the CXRB, the X-ray efficiency is substantially higher and in some cases the X-rays start competing with UV in the quest for reionizing the universe (see the  $x_{\text{ion}}^X$  column in Table 1). Partial ionization by X-rays is especially high in the case of the soft spectrum due to the extremely high X-ray efficiency in combination with the rapid, efficient absorption of soft X-rays by neutral gas. For instance, by the end of the UV reionization it reaches  $x_{\text{ion}}^X \sim 40$  per cent in the case of atomic cooling scenario.

For XRBs and mini-quasars,  $x_{\text{ion}}^X$  grows to 13.5 and 10.5 per cent, respectively, by the end of UV reionization (for the case of atomic cooling and early reionization). It is interesting to note that while UV photons heat and ionize the gas close to the source (given their very small mean free path within neutral gas), X-rays travel larger distances before inputting their energy in the IGM. As a result, in the extreme cases with high  $f_X$ , reionization is much more homogeneous, and may even proceed outside-in (Mesinger et al. 2013; Majumdar et al. 2016) instead of the conventional inside-out picture (Barkana & Loeb 2004).

### 4.2 21-cm signal

The brightness temperature of the 21-cm signal, observed with the CMB as a diffuse background source, is expected to be a three-dimensional probe of the high-redshift Universe. Current and planned telescopes are designed to measure the redshift evolution of this signal averaged over two-dimensional spheres (the global spectrum) as well as its spatial fluctuations at each given epoch which will allow us to extract the power spectrum. The predicted global spectrum contains information about milestones in the evolution of the Universe and for a wide range of models exhibits a prominent absorption trough which single-dish radio telescopes seek to observe. The sky-averaged brightness temperature reaches its minimal value at the point when heating sources turn on and begin raising the temperature of the IGM towards  $T_{\text{CMB}}$ . The power spectrum at each comoving wavenumber,  $k$ , when plotted as a function of redshift, shows a sequence of peaks driven by various spatially and temporally varying physical quantities (such as the kinetic gas temperature, fraction of neutral gas, and intensity of Ly- $\alpha$  radiation) which determine the intensity of the 21-cm transition. A generic plot of this type for the 21-cm power spectrum has three peaks (Barkana & Loeb 2005; Pritchard & Furlanetto 2007; Pritchard &



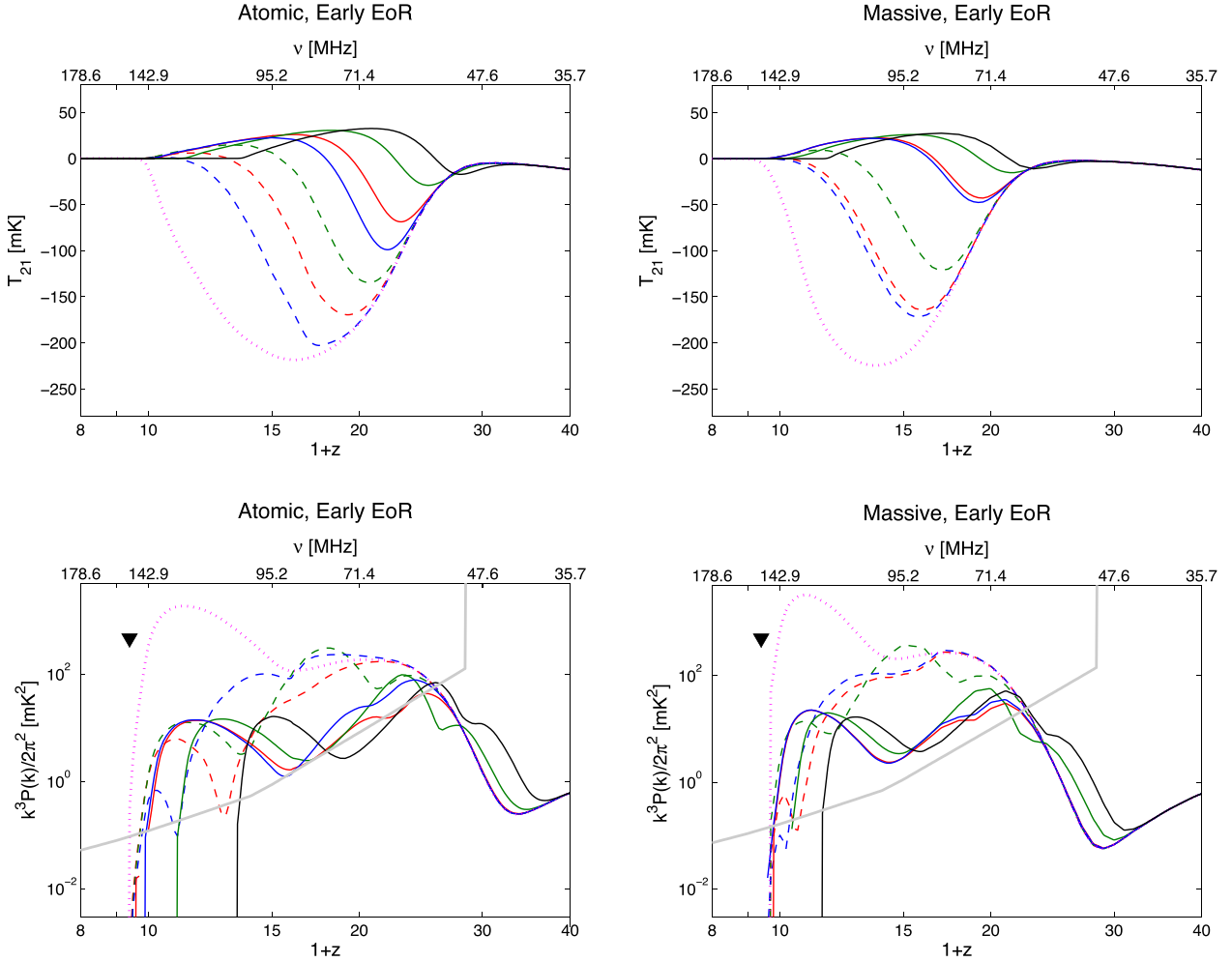
**Figure 3.** Global 21-cm brightness temperature (top) and its power spectrum in mK<sup>2</sup> units at  $k = 0.2 \text{ Mpc}^{-1}$  (bottom) are shown for the atomic (left) and massive (right) cases for our late reionization case ( $z_{\text{re}}^{\text{UV}} = 6.2$ ). We show the cases of X-ray sources with a soft SED (green), XRBs with a hard SED (red), or mini-quasars (blue), each for  $f_X = 1$  (dashed) or  $f_X$  normalized to its maximum value based on the CXRB (solid). The red dotted line shows the case with a low heating efficiency of  $f_X = 0.0095$  (0.036) for atomic cooling (massive haloes) with a hard X-ray SED. The black triangle marks the upper limit on the 21-cm power spectrum at  $z = 8.4$  (Pober et al. 2015) and the black dotted line shows the case of no heating,  $f_X = 0$ , which has been ruled out by this observation. In both the atomic and massive cases, the black solid line shows the case of extreme heating ( $f_X = 1000$ , soft SED) which overpredicts the CXRB. Finally, the thick grey line shows the power spectrum of the thermal noise for phase 1 of SKA-low assuming a single beam, 1000-h integration time, and a 10 MHz bandwidth.

Loeb 2008): the high-redshift peak, at  $z \sim 20\text{--}30$ , is due to Ly- $\alpha$  fluctuations; the mid-redshift peak, which is due to heating fluctuations, appears at  $z \sim 15\text{--}22$ , but this peak is not present on scales below the X-ray mean free path (Fialkov & Barkana 2014); and the low-redshift peak, at  $z \sim 7\text{--}10$ , is due to ionization fluctuations of the main targets of the present-day and future radio interferometers.

In Figs 3 (for the late reionization scenario) and 4 (which assumes early reionization), we plot the global spectrum of the 21-cm signal and its spherically averaged power spectrum, with the X-ray efficiencies normalized to the CXRB as well as the cases with  $f_X = 1$ ,  $f_X = 0$  and  $f_X = 1000$  shown for comparison. The latter case (which we shown only for the soft SED) clearly overproduces the observed CXRB, while the case of  $f_X = 0$  and late reionization is excluded by the PAPER observations. We do show these cases to demonstrate the effect of either extremely strong or absent X-ray heating (the excluded cases are shown with black lines in Figs 3 and 4). In addition, for the late reionization scenario and hard SED shown in Fig. 3, we demonstrate the 21-cm signal with the lowest possible

X-ray efficiencies (red dotted lines) normalized to the current PAPER limits (black triangle) as discussed at the end of Section 3. Finally, we plot the expected thermal noise power spectrum of phase 1 of the SKA assuming a single beam, an integration time of 1000 h, and a 10 MHz bandwidth. In the case of global 21-cm experiments, in principle, short integration times (minutes) suffice to detect the signal with a single dish (Shaver et al. 1999). In practice, though, the need for accurate calibration and precise removal of the spectrally smooth foreground make these measurements quite difficult, especially given the complex coupling of the errors at different frequencies. Quantitative analyses show that if calibration can remove any sharp frequency response, then it is possible to overcome the issues of a smooth foreground and thermal noise, and global signals such as those we predict in this paper should be detectable (Pritchard & Loeb 2010; Morandi & Barkana 2012; Liu et al. 2013; Bernardi et al. 2016).

We find that the cases of enhanced heating of the IGM strongly affect the expected global 21-cm signal. In particular, because the



**Figure 4.** Global 21-cm brightness temperature (top) and its power spectrum in mK<sup>2</sup> units at  $k = 0.2 \text{ Mpc}^{-1}$  (bottom) are shown for the atomic (left) and massive (right) cases for our early reionization case ( $z_{\text{re}}^{\text{UV}} = 8.5$ ). We show the cases of X-ray sources with a soft SED (green), XRBs with a hard SED (red) or mini-quasars (blue), each for  $f_X = 1$  (dashed) or  $f_X$  normalized to its maximum value based on the CXRB (solid). The magenta dotted line shows the case with no heating, i.e.  $f_X = 0$ . The black triangle marks the upper limit on the 21-cm power spectrum at  $z = 8.4$  (Pober et al. 2015). In both the atomic and massive cases, the black solid line shows the case of extreme heating ( $f_X = 1000$ , soft SED) which overpredicts the CXRB. Finally, the thick grey line shows the power spectrum of the thermal noise for phase 1 of SKA-low assuming a single beam, 1000-h integration time, and a 10 MHz bandwidth.

gas does not have sufficient time to cool down prior to being heated by X-rays, the absorption trough becomes shallower and thus harder to observe, requiring a higher precision of calibration and longer integration times. For instance, in the case of late reionization and atomic cooling, the minimal brightness temperature is reduced by  $\sim 64$  percent for a soft SED and  $\sim 37$  percent for a hard SED. In addition, the absorption trough is shifted to lower frequencies: from 70 to 60 MHz ( $\Delta z \sim 3.1$ ) in the case of the soft SED, from 74 to 66 MHz ( $\Delta z \sim 2.4$ ). Finally, with the enhanced heating the emission signal is much stronger and the peak shifts to higher redshifts; for each model, the maximal possible value of the emission signal is realized when the normalization is set so as to produce the full unresolved CXRB. In particular, in the case of late reionization and atomic cooling, the maximal brightness temperature is boosted by a factor of  $\sim 2$  ( $\sim 1.6$ ) for XRBs (hot gas). See Tables 1 and 2 for more information.

As discussed above, X-rays speed up reionization and the intensity of the 21-cm signal drops faster than otherwise expected towards the end of the reionization era, which is most noticeable in the cases with soft X-rays and maximal efficiency (set to the

full CXRB), as well as in the excluded case of extreme heating (with  $f_X = 1000$ ) where reionization ends considerably earlier than in other models. In addition, Ly- $\alpha$  photons generated by X-rays in the neutral IGM through relaxation of hydrogen atoms excited by primary photoelectrons are boosted by a factor of  $f_X$  in each case. For  $f_X = 1$ , these photons are far less important than Ly- $\alpha$  directly generated by stars; however, for  $f_X \sim \mathcal{O}(100)$  the contribution of these two sources becomes comparable. In this case, the 21-cm signal couples to the temperature of the gas (Wouthuysen 1952; Field 1958) earlier than it would for  $f_X = 1$ , which can be seen in Figs 3 and 4 for the cases with soft X-rays and CXRB normalization as well as the extreme heating case.

One of the striking consequences of the high X-ray efficiency on the power spectrum is that the amplitude of the 21-cm fluctuations is suppressed at high redshifts ( $\sim 15$ – $25$ ), making their detection from this epoch harder. In particular, the Ly- $\alpha$  peak at  $z \sim 25$  may become unobservable in the case of the soft SED. This happens mainly because the Ly- $\alpha$  fluctuations are anticorrelated with fluctuations seeded by inhomogeneous heating (prior to the heating transition), which is partially compensated by the enhanced generation of



Ly- $\alpha$  photons by X-ray excitation of the IGM. In most cases, there remains a significant signal from cosmic dawn observable with the SKA, even in these worst-case scenarios (in terms of observing cosmic dawn). Comparing the three cases of  $f_X = 1$ , 29.5 and 1000 with a soft SED, atomic cooling and late EoR, we see that the Ly- $\alpha$  peak drops from 95 mK<sup>2</sup> at  $z = 22.6$  ( $f_X = 1$ ) to 17 mK<sup>2</sup> at  $z = 25.6$  ( $f_X = 29.5$ ) and to 12 mK<sup>2</sup> at  $z = 28.6$  ( $f_X = 1000$ ). The effect of X-rays on the heating peak in the 21-cm power spectrum is also dramatic. The heating peak is lower and is shifted to higher redshifts (lower frequencies) when X-rays are strong. In the just-considered case of soft X-rays, atomic cooling and late EoR, the heating peak drops from 304 mK<sup>2</sup> at  $z = 16.9$  ( $f_X = 1$ ) to 155 mK<sup>2</sup> at  $z = 21$  ( $f_X = 29.5$ ) to 70 mK<sup>2</sup> at  $z = 24.7$  ( $f_X = 1000$ ). Thus, when the X-ray SED is soft, the normalization to the full unresolved CXRB yields a lower limit for the amplitude of the Ly- $\alpha$  and X-ray heating peaks in the 21-cm power spectrum and an upper limit for the redshift at which these peaks are located. In the case of a hard SED, the main effect of X-rays is to suppress the Ly- $\alpha$  peak, as the fluctuations in temperature are washed out by the large mean free paths of the X-ray photons and the heating peak is not always present. The intensity of the 21-cm fluctuations from lower redshifts ( $z \sim 10$ ) depends on both reionization and heating and, thus, is less straightforward to relate to the nature of the X-ray sources. In some cases, the fluctuations are enhanced, because the heating is closer to being saturated during the reionization era; in others, the fluctuations are suppressed as a result of the X-ray contribution to reionization.

Heating sources with extremely low X-ray efficiencies do not have enough time to heat the IGM before the end of reionization, and in this case the gas remains colder than the CMB even at that time. As a result, the absorption trough in the global spectrum is very deep, and the power spectrum features only two peaks sourced by inhomogeneous Ly- $\alpha$  and ionizing backgrounds. The latter peak is so strong in the case of  $f_X = 0$  that it can be ruled out using current upper limits on the 21-cm power spectrum at  $z = 8.4$  from PAPER as we have discussed at the end of Section 3. The minimal possible 21-cm brightness temperature reaches the value of  $T_{21} = -231.7$  mK ( $-237.3$  mK) at  $z_{\min} = 14.2$  (12.5) for atomic cooling (massive haloes) with a late EoR and  $T_{21} = -218.6$  mK ( $-224.6$  mK) at  $z_{\min} = 15.2$  (12.8) for atomic cooling (massive haloes) with an early EoR.

An intriguing result of our study is that, once available, the 21-cm global signal can be combined with the X-ray background produced by high-redshift sources to put constraints on the SED of these sources. Because hard sources are more efficient in seeding the CXRB, the CXRB limit implies a deeper 21-cm trough (as the universe is colder) than is possible in the case of soft X-ray sources. In particular, focusing on our case of the atomic cooling haloes and late EoR, we see that given the level of the X-ray background, the absorption trough in the case of XRBs reaches at least  $-107.4$  mK, which is much deeper than the corresponding limit in the case of the soft X-rays,  $-48.8$  mK. Therefore, observing a trough shallower than  $-107.4$  mK would rule out such a population of X-ray sources with a hard SED. In the future, with the direct high-redshift X-ray observations of X-ray Surveyor or Athena and the observed global 21-cm at hand, it will be possible to significantly constrain the properties of the high-redshift sources even without using any additional information. This method thus provides an important alternative to probing the nature of X-ray sources with the 21-cm power spectrum (Pritchard & Furlanetto 2007; Pacucci et al. 2014; Fialkov et al. 2015; Ewall-Wice et al. 2016). Moreover, having at hand the CXRB together with both the global 21-cm signal

and its power spectrum can help to break degeneracies between X-ray heating and other model parameters. We leave a more detailed discussion of this to future work.

Finally, based on the whole ensemble of models considered here, it is possible to define a border line of the parameter space within which the 21-cm signal can vary without violating any existing observational constraints. For instance, from the data presented in this paper, we see that the absorption trough of the global signal cannot be shallower than  $-15$  mK or deeper than  $-238$  mK, and it is located between  $z = 12.5$  and  $24.1$ . This border line can be used to guide future observations. Because the bank of models presented in this paper is limited, a more detailed discussion of this idea can be found in Cohen, Fialkov & Barkana (2016b) and our future work.

## 5 CONCLUSIONS

The main results of this paper are the consequences of the upper limit on the X-ray efficiency which various high-redshift hard or soft X-ray sources may have without violating the observed soft unresolved X-ray background. This limit allows us to estimate the maximal effect that early X-ray sources can have on the high-redshift 21-cm signal, reionization, the CMB, and the thermal history of the early Universe. Our results are particularly useful in light of the existing and upcoming radio telescopes designed to probe these early epochs.

We find that different types of high-redshift X-ray sources considered here (i.e. XRBs, hot gas, or mini-quasars) naturally produce an X-ray background with a slope close to that of the observed unresolved soft CXRB, which, however, is poorly constrained by present observations. Therefore, it is hard to reach strong conclusions about the nature of X-ray sources based on the current measurements of the shape of the CXRB. On the other hand, normalization to the X-ray background does constrain the maximum possible X-ray efficiency which the high-redshift heating sources can have. Hard X-ray sources are more efficient in producing the observed background, compared to the soft sources, and so the maximal X-ray efficiency is typically around two to three times lower for hard sources than for the soft ones. More generally, the X-ray efficiency that is needed to explain the CXRB is very high compared to what is normally assumed based on low-redshift observations. This allows for a possibility that the high-redshift sources may be more luminous than their low-redshift counterparts. For a population of X-ray sources assumed to have existed down to redshift 6.2 (and then cut-off), this enhancement factor varies between  $\sim 10$  and  $\sim 40$ , for the various cases; for a population that only existed at  $z = 8.5$  and above, the factor is in the range  $\sim 44$ – $190$ .

Based on our most extreme case (the early reionization scenario with massive haloes only), we can put a realistic upper bound on the bolometric luminosity of the high-redshift sources per SFR:  $\sim 2.4 \times 10^{42}$  erg s<sup>-1</sup> M<sub>⊙</sub><sup>-1</sup> yr for XRBs,  $\sim 5.6 \times 10^{42}$  erg s<sup>-1</sup> M<sub>⊙</sub><sup>-1</sup> yr in the case of hot gas, and  $\sim 2.6 \times 10^{42}$  erg s<sup>-1</sup> M<sub>⊙</sub><sup>-1</sup> yr for mini-quasars (assuming the luminosity – SFR relation of proportionality). Interestingly, recent observations suggest that hard X-ray sources such as XRBs or accreting black holes are a factor of  $\sim 10$  more luminous in metal poor than in solar-metallicity galaxies (Prestwich et al. 2013; Brorby, Kaaret & Prestwich 2014). In addition, X-ray sources in low-redshift dwarf galaxies appear to be ultraluminous (Lemons et al. 2015). However, these trends would have to greatly increase in order to approach the upper bounds that we find.

The possible enhanced heating at high redshift has direct implications for the thermal history and the reionization of the IGM as well as for the 21-cm signal produced by neutral hydrogen

during and prior to cosmic reionization. In particular, cosmic heating can happen up to  $\Delta z \sim 4\text{--}5$  earlier than what is normally assumed. However, even with the enhanced X-ray emission the saturated heating assumption throughout reionization can only be used with soft sources. In addition, efficient X-ray sources compete with stellar sources in ionizing the gas. In particular, X-ray sources with soft spectra can be so efficient as to compete with UV photons in reionizing the universe, producing a fractional increase in the optical depth to CMB photons of 12–16 per cent. In the cases when X-rays are so efficient, reionization happens more homogeneously since X-rays have a very long mean free path compared to UV and, thus, ionize the IGM far from the sources. On the other hand, hard sources such as XRBs and mini-quasars (with their maximal normalization) have only a mild effect on reionization, producing a fractional increase in the CMB optical depth of only 1–3 per cent.

Thus,\* in our model, reionization is mainly driven by stellar sources which emit UV, while quasars can have a small impact on the EoR channelling their energy into hard X-rays. A different situation was described recently by Madau & Haardt (2015) who explored a possibility of reionization achieved only by high-redshift quasars and other faint, high-redshift AGN. Madau & Haardt (2015) assigned a composite emissivity to their quasars accounting for a broad spectrum of emitted photons, from optical to hard X-rays (Haardt & Madau 2012), which resulted in a stronger contribution of AGN to reionization. These authors found that  $z > 5$  active galaxies can reionize the universe without overproducing the unresolved CXRB at 2 keV (amounting to  $\sim 60$  per cent of the CXRB) provided their properties are similar to those of their lower redshift counterparts. The contribution of high-redshift quasars in this case was normalized by fitting the observed integrated optical emissivity at redshifts up to  $\sim 5$  (Bongiorno et al. 2007; Schulze et al. 2009; Giallongo et al. 2015) and extrapolating this result to higher redshifts out to  $z \sim 12$ . This emissivity drops slowly with redshift, predicting a significant population of quasars at early times. Based as it is on the extrapolation of current scarce high-redshift observations, this result may overestimate the role of quasars and AGN in reionization.

An important implication of the possible high X-ray efficiency of the early X-ray sources is the signature that they imprint in the 21-cm signal of neutral hydrogen. This signal has not been detected yet, and its discovery is a major goal of the astronomical community. Since the agents of high-redshift cosmic heating are highly unconstrained, a wide space of possibilities is left for the 21-cm signal, which translates into a wide parameter space for telescopes to search. Having an upper limit on the effects of cosmic heating naturally constrains the search parameter space and can help guide telescope design and search strategies. An upper limit on heating has important implications both for the global spectrum and for the spatial fluctuations of the 21-cm signal.

In the case of a high X-ray efficiency, the absorption trough of the global 21-cm signal is significantly reduced and shifted towards lower frequencies (higher redshifts), while the reionization gradient (in emission) is extended over a broader range of frequencies. The 21-cm power spectrum is suppressed at high redshifts ( $z \sim 15\text{--}25$ ) due to the enhanced heating, and the Ly- $\alpha$  peak is reduced and shifted to lower frequencies as well as the X-ray peak (if present); however, the fluctuations from the second half of reionization are maintained and sometimes boosted due to the effect of saturated heating. Thus, there is mixed news for 21-cm experiments. For global experiments, the expected signal from reionization and cosmic dawn is bounded and for some models can be significantly reduced. For phase 1 of the SKA, reionization remains observable

at a high signal-to-noise ratio in all cases, but cosmic dawn can become difficult to observe in the most extreme cases. We note that in our calculation we do not account for exotic processes, such as dark matter annihilation, which could heat up the gas early on and suppress the 21-cm signal without leaving any X-ray background.

For completeness, we have also considered lower limits on the X-ray heating efficiency for late reionization scenarios (which do not end before  $z = 8.4$ ) using recent upper limit found by PAPER. Weak or no X-ray heating results in a 21-cm signal with a deep absorption trough in the global signal and strong fluctuations from all the epochs that normally have a signal that is suppressed due to cosmic heating. Such a signal should be an easy target for radio telescopes.

To summarize, the unknown details of star formation, the process of reionization and the nature of high-redshift X-ray sources, including their SED and X-ray efficiency, result in a large uncertainty in the expected 21-cm signal. Specifically, the absorption trough, the main feature of the global 21-cm signal, can vary in depth anywhere from  $T_{21} \sim -240$  to  $-15$  mK, and in position from  $z \sim 12$  to 24; the fluctuation peak from mid-reionization is still unconstrained to better than the range of  $3\text{--}3000$  mK<sup>2</sup> at  $k = 0.2$  Mpc<sup>-1</sup>; the X-ray peak strongly depends on the properties of the X-ray sources and can be strong, mild or vanishing; finally, the strength of the fluctuation peak from the Ly- $\alpha$  coupling era varies between 2 and 200 mK<sup>2</sup> and its redshift lies within  $z \sim 13\text{--}25$ .

While the CXRB narrows the possible realization space of the 21-cm background only slightly at present, future X-ray missions such as Athena and X-ray Surveyor could directly probe high-redshift sources of X-rays, constraining their effect on the intergalactic gas and the 21-cm signal.

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